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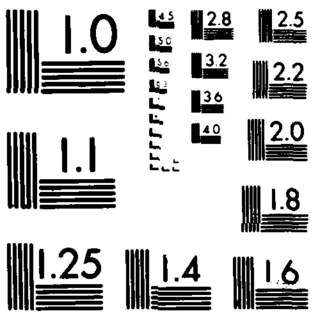

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AERONAUTICAL RESEARCH LABORATORIES

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STRUCTURES REPORT 383

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by

J. M. FINNEY

Approved for Public Release.

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ANALYSIS OF RESULTS FROM AN INTERNATIONAL FATIGUE TEST PROGRAMME

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J. M. FINNEY

SUMMARY

Under the auspices of the Commonwealth Advisory Aeronautical Research Council fatigue tests ~~had been~~ made on identical 2L.65 aluminium alloy specimens in the UK, Canada and Australia; this report statistically examined the results to determine whether the same answer may come from nominally the same fatigue experiment. Viewing the complete set of data any differences between the results of the various countries were not significant. Viewing limited portions of the data some differences were significant. Variance differences were significant only at the lower stress levels used and involved predominantly UK (first set) and Canadian results. Differences between means were significant only at the upper stress levels used and involved predominantly Australian and UK (second set) results.

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16. *ABSTRACT*

Under the auspices of the Commonwealth Advisory Aeronautical Research Council fatigue tests had been made on identical 2L.65 aluminium alloy specimens in the UK, Canada and Australia; this report statistically examined the results to determine whether the same answer may come from nominally the same fatigue experiment. Viewing the complete set of data any differences between the results of the various countries were not significant. Viewing limited portions of the data some differences were significant. Variance differences were significant only at the lower stress levels used and involved predominantly UK (first set) and Canadian Results. Differences between means were significant only at the upper stress levels used and involved predominantly Australian and UK (second set) results.

CONTENTS

1. INTRODUCTION

In 1960 under the auspices of the Commonwealth Advisory Aeronautical Research Council (CAARC) a "Fatigue Research Calibration Project" was initiated. The purpose of this project was to determine whether the normal fatigue test methods in use in different countries produce the same answer from the same experiment. This "calibration" was regarded as a necessary preliminary step to the conduct of joint fatigue research programmes.

The original participating organisations and countries are: Royal Aircraft Establishment, United Kingdom; National Aeronautical Establishment, Canada; and the Aeronautical Research Laboratories, Australia. A suitable specimen was designed and a number were manufactured in the UK and distributed to the other countries. The three countries made tests under the same stressing conditions, each using their own procedures and test machines.

Each country has reported its own test results[1,2,3] but, heretofore, no analysis has been made which addresses the original objective. This objective is still relevant, however; it is still pertinent to question whether fatigue results contain a "laboratory" effect.

Recently India joined the programme and is planning to make tests similar to those made in the other countries. Prior to this programme a brief statistical appraisal was made by the Indian Civil Aviation Department[4] of the test results available from the other countries, but this examination focused attention on the peripheral question of bi-modal life distributions at certain stress levels. It did not attempt to examine the results in the framework of the original objective. The present report is such an examination.

2. MATERIAL AND TEST SPECIMENS

The rather large fatigue specimens, illustrated in Figure 1*, were made in the UK from BS 2L.65 aluminium alloy extrusions from one cast. The extruded bars were numbered 1 to 10, 12 to 15, 17, and 19 to 33. Specimens were identified first by the bar number, then from 1 to 10 according to the position along the bar, commencing from the front end of the extrusion.

The test section of the specimens is almost square and contains a drilled and reamed transverse hole giving a theoretical stress concentration factor (K_t) of approximately 2·3.

The cast chemical analysis and tensile properties of the extruded bars supplied by the manufacturer (taken from Reference 5) are given in Appendix 1.

3. FATIGUE TESTS

Fatigue tests were made in each country at a mean stress on the net section of 16 ksi (110 MPa) and alternating stress amplitudes (S_a) of 14, 12, 10, 9 and 8 ksi (97, 83, 69, 62 and 55 MPa) although some tests were run at lower amplitudes. On the average about five specimens were tested at each stress level by each country, and there was an attempt to evenly distribute the bar and position numbers of the specimens among the stress levels.

All UK tests were made in a 20 ton (199 kN) Avery Schenck axial-load resonance machine operating at a frequency of about 35 Hz. Universal fittings were used between the lug ends of the specimen and fork ends of the test machine to minimise bending stresses. The machine was calibrated before each series of tests.

The UK made two series of tests in this machine, separated by a five-year period; the only other noticeable difference between the series was the operator. In the first series of tests there was a tendency for failures at lower stress levels to occur at the lug ends of the specimens rather

* The testing programme was defined and completed while Imperial units were commonly used. Dimensions, stresses, etc., are stated in this report in those units, with S.I. equivalents indicated in parentheses.

that at the central test section with the notch. In the second series kite-shaped pins were used in the lug ends in place of the original circular-section pins and no lug-end failures were reported.

The Canadian tests were made in a Sonntag SF10-U fatigue machine fitted with a multiplying fixture giving a maximum load capacity of 50,000 lb (222 kN). The cyclic frequency was 30 Hz and the specimens were clamped rigidly in the grips of the testing machine. Only one grip-end failure occurred using this clamping system. The accuracy of loading was verified by using a strain-gauged dummy specimen having dimensions similar to the 2L.65 test specimens but made from 24S-T4 aluminium alloy. This specimen was calibrated in tension and bending using a deadweight facility. In the Canadian tests failure was defined as complete separation of the halves of the specimen.

The Australian tests were made in a 100 ton (980 kN) Amsler hydraulic pulsator. The first three tests (specimens F13/1, 1/8 and 6/6) were made at a cyclic frequency of 8 Hz and the remainder at 4 Hz. Loading was through a simple pin joint with the hardened steel pins having diametrically opposite flats to alleviate fretting. Many of the specimens tested initially failed at the lug ends of the specimens and this problem was ultimately overcome by plastically expanding the lug holes with a mandrel.

The cycles to failure for the Australian test specimens were the numbers recorded upon operation of the machine cut-off system. This usually occurred after the development of a substantial crack or cracks but before separation of the specimen into two pieces.

During the Australian test programme a static load calibration of the pulsator was made and it was found to be accurate to within $\pm 1\%$ for all its load ranges. One fatigue specimen was also strain-gauged to measure tension, side and face bending, and torsional strains. Several series of *static* strain measurements were made with this specimen covering the range of loads used in the fatigue testing. For both bending directions the bending strains, as a proportion of the tensile strain, decreased as the tensile strain increased. The highest proportions were recorded at a load of 10,000 lb (44 kN) and were an average of $4{\cdot}5\%$ for face bending and $1{\cdot}9\%$ for side bending.

4. FATIGUE TEST RESULTS

The test results reported by the three countries[1,2,3] are listed in Tables 1 to 4. Figures 2 to 6 show plots of these results ignoring retests after run-outs. The mean curves shown are best-fit polynomials based on the logarithm of life and taking the run-out and lug-end values as test section failures. At each stress level the points were weighted by the reciprocal of the variance at that level. Figure 7 gives a composite of all the results using the same conditions of plotting and curve-fitting. (Weighting was inapplicable for the Australian (and hence the composite) test results since at many of the stress levels there were variations in the stress values used.)

5. STATISTICAL ANALYSES

5.1 Data Groups

Since the objective was to compare the fatigue test results of the various countries, a number of groupings of the data were necessary. These groupings arise for the following reasons.

(*a*) Two series of tests were made by the U.K. and it is valid to treat them either collectively or separately.

(*b*) Not all specimens failed in the test section: some failed in the grips and others remained unbroken after lengthy testing.

(*c*) Run-outs and lug-end failures may be considered in two ways. Their lives may be taken simply as another test section failure at the appropriate stress level. Or they may be used to estimate the life at which a failure in the test section would have occurred but for stopping the test.

(*d*) Most Australian tests were made at alternating stress levels a little different in magnitude from those used by the other countries, and for valid comparisons it is necessary

to shift these results to common stress levels. There are various possibilities, however; for example, a result at $S_a = 8 \cdot 5$ ksi (59 MPa) may be moved to either 8 or 9 ksi (55 or 62 MPa).

For the statistical analyses the main groupings of the data, both combining and separating the two UK series of test results, were:

(*a*) test section failures;

(*b*) test section failures + run-outs;

(*c*) test section failures + run-outs + lug-end failures.

In addition, and where appropriate, subdivisions were made to incorporate:

(i) upgraded lives when run-outs and/or lug-end failures occurred at the stress level being considered, and

(ii) various shifts of the Australian results, achieved by using the shapes of the best-fit polynomials and moving the results to the nearest common stress level.

During the test programmes one specimen tested by Canada and six specimens tested by Australia, which were unbroken after a long life at a low stress level, were retested until failure at higher stress levels. These retest results were not used in the present analyses.

5.2 Statistical Tests and Results

For concise description, the various countries are denoted UK1 (UK series 1), UK2 (UK series 2), UK (both UK series), CAN, AUS.

All fatigue life data were analysed using the logarithm of the number of cycles and a significance level of 0·05 (it was appropriate to use a two-tail test for the pairwise comparisons described below and a one-tail test for the various analyses of variance). The various manipulations of the data and the statistical tests used for comparisons are described in Appendix 2.

Within the groupings listed in Section 5.1 the data were compared at three conceptual levels as described in the following sections.

5.2.1 Pairwise Comparisons at Each Stress Level

At each stress level, for pairwise countries (eight valid pairs), variances and means were compared using F and t tests respectively. These comparisons allow the typical questions to be answered—Is the mean of UK1 different from the mean of CAN at $S_a = 9$ ksi (62 MPa)? Is the variance of the UK results at $S_a = 14$ ksi (97 MPa) different from that of the Australian results?

When the variance ratio (F) test indicated a significant difference between the variances of a pair, a modified t-test which allows for this fact was used (see Appendix 2).

The result of these comparisons for the various combinations of country pairs and data groups are given in Tables 5 to 11. For 91% of the unique combinations listed there is no significant difference between the variances, and for 74% of the unique combinations there is no significant difference between the means.

The influence of variously shifting the AUS results may be obtained from these tables. For the unique pairwise comparisons involving AUS data the variance ratio test gave a different result only in 6% of the cases when a different shifting of the AUS data was used. Similarly, the result of significance testing the means was different in only 4% of the cases. Thus, whether one arrangement or another was used for moving AUS results to common stress levels, the effect on pairwise comparisons was minimal.

There is no change to the pairwise comparisons by upgrading the means and variances when run-outs and/or lug-end failures occurred—compare Table 11 with Table 10. (Three of the 11 country/stress level combinations suitable for estimating upgraded values were not used in compiling Table 11 and this point is discussed in Appendix 2).

5.2.2 Analysis of Variance at Each Stress Level (One-way ANOVA)

For each stress level an analysis of variance was made to determine whether differences between the means of the various countries were significant or not; i.e. whether the differences were greater or were within the range expected from error (scatter of lives). In cases where the differences between the means were significant, "Contrasts", see Appendix 2, were used to determine which set(s) of results caused the differences to be significant.

The ANOVA results are given in Tables 12 and 13 for four and three "countries" respectively. Differences between the means of the countries occur only at 12 and 14 ksi (83 and 97 MPa). At 12 ksi (83 MPa) it is always the AUS mean which is different from the means of the other countries. Similarly at 14 ksi (97 MPa), and where differences are significant, the AUS mean is different from the means of the others, and, in the four-country comparison at this stress, the UK2 mean is also different from the means of the others. (In this case, i.e. where both AUS and UK2 are different from the others, it is noted that these differences may well be correlated.)

This result is contained already, although not definitively, in the pairwise comparisons of the previous section. Table 14 lists the number of times each country was involved in significant differences between pairwise means. It is clear that differences occur only at 12 and 14 ksi (83 and 97 MPa); at 12 ksi (83 MPa) AUS is the likely divergent country, and at 14 ksi (97 MPa) both UK2 and AUS are likely divergent countries.

5.2.3 Analysis of Variance Over All Data (Two-way ANOVA)

An analysis of variance was made viewing the data from each country as a whole, using a two-way classification (country/stresses). This perspective allows the question to be answered—overall, and by eliminating the effects of stress level, is there any difference between the fatigue data from the various countries? In addition, the analysis (Appendix 2) allows the determination of any significant interaction, i.e. a determination of whether some countries perform either better or worse than the others at some stress levels but not at others.

Again, the data groups were subdivided into three and four countries, using various shifts of the AUS data. Only data at stress levels common to all countries were used; in all cases considered the stress levels used were 9, 10, 12 and 14 ksi (62, 69, 83 and 97 MPa).

The results are given in Table 15. In all the cases examined there is no significant difference between the fatigue data from the various countries (after eliminating the effects of stress level), neither is there any country/stress interaction.

6. DISCUSSION

6.1. Overview of Results

The question examined by the testing programme undertaken in the various countries, namely, whether the fatigue test methods used in the different countries would produce the same answer from the same experiment, can be answered in the affirmative when a global view of the test results is taken.

There are, however, some differences in the experimental results when viewing only portions of the data. Significant differences in variances occurred only at the lower stress levels (9 and 10 ksi (62 and 69 MPa)) and involved predominantly UK1 and CAN results. Significant differences in means occurred only at the upper stress levels (12 and 14 ksi (83 and 97 MPa)) and involved predominantly UK2 and AUS results.

6.2. UK Test Results

The UK1 and UK2 results are equivalent at the intermediate stress levels of 10 and 12 ksi (69 and 83 MPa), but not at the extreme levels of 9 and 14 ksi (62 and 97 MPa). At 14 ksi (97 MPa) no matter how the data were grouped, the mean of UK1 was always significantly different from the mean of UK2. At 9 ksi (62 MPa), and for the grouping of "test section failures" only, the variances were significantly different. On the other hand, by analysing all the UK data

with the two-way classification technique as described in Append ᐧ 2, the hypothesis that UK1 = UK2 cannot be rejected, no matter how the data were groupec.

6.3 Factors Contributing to Differences

By focusing attention on those cases where differences exist in the results it is worth briefly examining some of the factors involved in the experiments which may have contributed to these differences. The several factors are:

(i) different methods of gripping and alignment;

(ii) inaccuracies in load setting;

(iii) different frequencies;

(iv) different failure criteria; and

(v) environmental variations.

These are now discussed in turn.

(i) Although the UK and Australia loaded the specimens through the pins, and Canada rigidly clamped the end sections, the loading method itself is important only as it bears on the alignment accuracy. This accuracy is unknown except for the Australian tests where the extent of extraneous loadings were noted (Section 3) as a maximum of 4·5% of the tensile stress for face bending.

Intuitively, misalignments can only decrease fatigue life, hence variability in the amount, from one test to another, should increase scatter and decrease mean life. The test results were examined at each stress level to determine any correlation between variance and mean life. No correlation was apparent and hence it cannot be claimed that variable misalignments contributed to the differences.

(ii) Although each country made load calibrations on their respective fatigue machines there is little indication of how accurately the loads were set and controlled, and, particularly with the older-type machines used in the investigation, some differences in accuracy may be expected. Even within recommended[9] loading accuracies differences in life of more than 2 : 1 could arise.[10]

With any of the machines used the percent variability in load setting may be expected to increase with decreasing applied load. This reasoning leads to a greater likelihood of differences among fatigue life scatter parameters at lower stresses which in fact occurs with the present test results. The pattern of variance differences obtained is thus consistent with the possibility of such differences arising from variable load settings.

(iii) The UK tests were made at a cyclic frequency of about 35 Hz, the Canadian tests at 30 Hz, and the Australian tests at 4 Hz (mostly). It is known that total fatigue life increases with frequency;[11-14] a typical example is given in Reference 14 where the average fatigue life of 2024 aluminium alloy specimens tested in rotating bending was doubled at lives less than 10^6 cycles by increasing the test frequency from 3 to 24 Hz. At lives greater than 10^6 cycles frequency had no effect. The material tested and the frequency range used in Referei .e 14 are similar to those used in the tests now being examined.

For stress level-by-stress level analysis of variance detailed in Section 5.2.2, and where significant differences in mean life were demonstrated, the AUS mean life was *always* the lowest ·he group. Moreover, the differences in mean life were significant only at the highest stress levels. These facts accord with the frequency effect noted above. (It could be countered that, in some of the cases where the AUS lives were the lowest of the group, the UK2 lives were significantly higher than the others and yet were obtained at the same frequency as UK1 and nearly the same frequency as CAN. To examine this counter-argument, one-way ANOVAs were made in these cases after excluding the AUS results. These analyses showed no difference between the UK1, UK2 and CAN results. It is concluded that when the UK2 mean life is significantly greater than the others, it is because of the inclusion of the low-life AUS results in the comparison, and not because of the UK1 and CAN results being significantly lower. The correlation of the pattern of mean lives above with known frequency behaviour thus stands.)

(iv) The failure criterion used by Canada was complete separation of the halves of the specimen; that used by Australia was the operation of a machine cut-off, usually after the development of a substantial crack but before complete separation; and the criterion adopted by the UK was not stated. The different criteria may have contributed to the differences between the fatigue results of the various countries but there is no way of quantifying the effect.

(v) Extreme values of humidity are known to change the mean fatigue life of aluminium alloys by a factor of two or more.[15,16] On this basis some interlaboratory environmental effect is expected in the present set of results, but again, as no measurements were reported, the effect cannot be quantified.

6.4 Comparison with Other Interlaboratory Fatigue Test Programmes

The basic question examined in this report has been the subject of other test programmes,[17–22] the conclusions from which are variable. Concentrating on those programmes which deal with total fatigue life, one of the earliest reported[17] was the S/N testing of identical 2024 and 7075 aluminium alloy sheet specimens at $R = 0$ and $R = -1$ by the Langley Aeronautical Laboratory and the Batelle Memorial Institute. Graphical comparisons of the results were made; there was excellent agreement at the middle range of stresses used but at the extremes deviations were apparent. At low stresses, and particularly with the 7075 material, it is obvious by inspection that the two laboratories produced significantly different results.

Other programmes have also indicated significant interlaboratory differences. Of eight laboratories in Canada[18] making identical tests using axially-loaded 2024-T4 sheet specimens, only three laboratories could be considered as giving results that could come from the same population. Seventeen European laboratories[19] participated in a programme under the auspices of the Organisation for Economic Co-operation and Development, each testing nine steel specimens in axial loading at each of three stress levels. A one-way analysis of variance determined no interlaboratory effect at the lowest of the three stress levels, but quite significant differences between the different laboratory results were evident at the two higher stress levels.

A more recent European interlaboratory programme[20] used axially-loaded welded steel specimens and covered six laboratories, two steels, three welding organisations, three types of weld, three R-ratios, and (generally) three stress levels. One conclusion from this programme was that neither the scatter nor the mean lives from the particular laboratories differed significantly.

In the main these various collaborative programmes come to the same conclusion as the present one, namely, that an interlaboratory effect is evident at some stress levels but not at others. However, the results of the recent European programme on welded steel specimens provide some optimism. It is suggested that, with the knowledge now available on the factors which may contribute to interlaboratory variability and which thus need to be controlled, and with recent improvements in load control on fatigue test machines, such variability in fatigue test data may now be eliminated.

7. CONCLUSIONS

Analysis of the results from fatigue tests made by the UK (two sets of results), Canada and Australia allow the following conclusions. (The tests were made on identical 2L.65 aluminium alloy specimens and mainly at stress levels of 9, 10, 12 and 14 ksi (62, 69, 83 and 97 MPa).)

(1) Viewing the data from each country as a whole, there is no significant difference between the results of the various countries (considered either as three or four sets of results) after eliminating stress level effects, neither is there any significant country/stress interaction.

(2) Viewing limited portions of the data, there are some significant differences between the results.

(*a*) With pairwise-country comparisons differences in variances were significant in 9% of the cases examined. These differences occurred only at the lower two stress levels (9 and 10 ksi (62 and 69 MPa)) and involved predominantly UK1 and Canadian results.

(*b*) With similar pairwise comparisons differences in means were significant in 26% of the cases examined. These differences occurred only at the upper two stress levels (12 and 14 ksi (83 and 97 MPa)) and involved predominantly UK2 and Australian results. This conclusion is supported by the results from an analysis of variance and the use of contrasts. When significant differences between means occurred it was always the Australian results, and sometimes the UK2 results also, which were different from the others.

(*c*) It was necessary to shift some of the Australian results to stress levels common with those used by the other countries; the shifting arrangements used had little effect on the pairwise comparisons.

(*d*) When run-outs and/or lug-end failures occurred, a maximum likelihood method was used to upgrade variances and means. There was no change in the results of the pairwise comparisons using these upgraded values.

(3) Similar conclusions are valid when comparing the two sets of UK results, namely, that viewed overall there is no difference between them, but when considered stress level-by-stress level the means were different at 14 ksi (97 MPa), and at 9 ksi (62 MPa) the variances were different.

(4) A number of factors were examined which may have contributed to these differences. The known effect of cyclic frequency is compatible with the pattern of significant differences among the present results and is the most likely reason for such differences. Load setting and controlling inaccuracies may also have contributed.

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REFERENCES

1. Kirkby, W. T. CAARC Fatigue Research Calibration Project – A Summary of UK Results. Commonwealth Advisory Aeronautical Research Council C.C. 724, April 1974.

2. Dunsby, J. A., and Walker, A. C. CAARC Co-operative Fatigue Test Programme – Canadian Results. National Research Council of Canada, Nat. Aeronaut. Establ. Lab. Memo. ST-130, September 1970.

3. Mann, J. Y., Harris, F. G., and Rowan, R. W. Fatigue tests on large notched specimens of 2L.65 aluminium alloy. Dept. Defence, Aeronaut. Res. Labs. Report ARL SM353, November 1974.

4. Ganesan, K. B., Ranganathan, N., and Saha, F. Statistical analysis of results of CAARC fatigue calibration programme. Civil Aviation Dept., Technical Centre T.R. no. 90, July 1977.

5. Buckley, L. E. Extruded aluminium alloy bar to specification 2L.65 and sections 1 and 6 of B.S. L100 supplied against R.A.N. order no. 1SC D 03345. James Booth Aluminium Ltd., Metallurgical Dept. Rep. no. RF 001, November 1961.

6. Miller, I., and Freund, J. E. "Probability and Statistics for Engineers." Prentice-Hall, Inc., Englewood Cliffs, N.J., 1965, p. 174.

7. Ford, D. G. Maximum likelihood estimators for truncated samples from normal populations. Dept. Supply, Aeronaut. Res. Labs. Report ARL SM264, October 1958.

8. Kempthorne, O. "The Design and Analysis of Experiments." John Wiley & Sons Inc., 1952, p. 79.

9. International Organization for Standardization. Axial Load Fatigue Testing. ISO Recommendation R 1099, July 1969.

10. Finney, J. M., and Mann, J. Y. Fatigue S N data in relation to variability in predicted life. "Aircraft Structural Fatigue." Proceedings of a symposium held in Melbourne, 19–20 October 1976. Dept. Defence, Aeronaut. Res. Labs. Struct. Rep. no. 363 Mat. Rep. no. 104, April 1977, pp. 149–76.

11. Krouse, G. N. A high speed fatigue testing machine and some tests of speed effect on endurance limit. Proc. Amer. Soc. Test. Mater., vol. 34, pt. 2, 1934, pp. 156–64.

12. Wade, A. R., and Grootenhuis, P. Very high speed fatigue testing. Proc. Int. Conf. Fatigue Metals. London, Instn. Mech. Engrs., 1956, pp. 361–69.

13. Awatani, J., Katagiri, K., Omura, A., and Shiraishi, T. A study of the fatigue limit of copper. Met. Trans. A., vol. 6A, 1975, pp. 1029–34.

14. Mann, J. Y. The effect of rate of cycling on the fatigue properties of 24S-T aluminium alloy. Dept. Supply, Aeronaut. Res. Labs. Report no. ARL SM 188, 1954.

15. Bennett, J. A. Changes in the influence of atmospheric humidity during fatigue of an aluminium alloy. J. Res. Natl. Bur. Stand.—C. Eng. and Instrum., vol. 68C, no. 2, 1964, pp. 91–100.

16. Hudson, C. M., and Seward, S. K. A literature review and inventory of the effects of environment on the fatigue behaviour of metals. Eng. Fract. Mech., vol. 8, 1976, pp. 315–29.

17. Grover, H. J., Hyler, W. S., Kuhn, P., Landers, C. B., and Howell, F. M. Axial load fatigue properties of 24S-T and 75S-T aluminium alloy as determined in several laboratories. Nat. Advis. Comm. Aeronaut. Rep. 1190, 1954.

18. Dunsby, J. A. A preliminary analysis of the results of some comparative fatigue tests conducted by eight Canadian laboratories. Nat. Aeronaut. Establ., Lab. Memo. ST-45, October 1962.

19. Bastenaire, F., and Bastien, M. Committee for Applied Research, Group of Experts on Fatigue Failure in Metals, Organisation for Economic Co-operation and Development, DAS/RS/62.1, February 1962.

20. Fatigue investigation of higher strength structural steels in notched and welded condition. Commission of the European Communities, Directorate General "Industrial and Technological Affairs", Doc. no. EUR 5357e, 1975.

21. Cazaud, R. Results of fatigue tests on welded joints combined from different countries (in French). Soudage Tech. Conn., vol. 11, no. 11-12, November-December 1957, pp. 386-90.

22. Clark, W. G., and Hudak, S. J. Variability in fatigue crack growth rate testing. J. Test. Eval. vol. 3, no. 6, 1975, pp. 454-76.

APPENDIX 1

Chemical Composition and Tensile Properties of 2L.65 Aluminium Alloy

(a) *Cast chemical analysis* (%)—Reference 5

	Cu	Mn	Mg	Fe	Si	Zn	Ti	Cr	Ni
Range	4·10 4·25	0·53 0·54	0·70 0·73	0·32 0·32	0·73 0·73	0·19 0·19	0·06 0·06	0·10 0·10	— —
Average	4·20	0·54	0·71	0·32	0·73	0·19	0·06	0·10	—
Spec. BS 2L.65	3·8 4·8	0·4 1·2	0·55 0·85	1·0 max.	0·6 0·9	0·2 max.	Ti+Cr 0·3 max.		0·2 max.

(b) *Tensile properties of extruded bars* – Reference 5.

		0·1% Proof stress		Ultimate tensile strength		Elongation (%)
		p.s.i.	MPa	p.s.i.	MPa	
Front end	Range	63,200 68,300	436 471	71,900 77,500	496 534	9 16·5
	Average	65,500	452	73,000	503	13
Back end	Range	64,100 69,000	442 476	72,100 75,500	497 521	9 16
	Average	66,100	456	73,300	505	13

APPENDIX 2

Statistical Techniques

A. Notation

x	Log_{10} (fatigue life)
$\bar{x}$	Log mean fatigue life
μ	Grand mean of log life
s^2	Sample variance of log life
σ^2	Population variance
n	Number of results
α	Level of significance
a	Treatment (country) effects
b	Block (stress level) effects
c	Interaction effects (between country/stress)
e	Error

Subscripts:

1, 2	Denote first sample, second sample, etc.
i	Denotes treatment (country) number
j	Denotes block (stress level) number
k	Denotes number of results within any treatment or within any (i, j) cell

B. Pairwise Comparisons

(i) *Comparison of variances:* F-*test*

For independent random samples from two normal populations with variance σ_1^2, σ_2^2 the null hypothesis that $\sigma_1^2 = \sigma_2^2$ is accepted against the alternative $\sigma_1^2 \neq \sigma_2^2$ when

$$s_1^2/s_2^2 \leqslant F_{\alpha/2, n_1-1, n_2-1} \qquad (\text{for } s_1^2 > s_2^2)$$

(ii) *Comparison of means:* t-*tests*

(*a*) For independent random samples from two normal populations *having the same variance*,

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\dfrac{(n_1-1)s_1^2 + (n_2-1)s_2^2}{n_1+n_2-2}}\sqrt{\dfrac{1}{n_1}+\dfrac{1}{n_2}}}$$

and the null hypothesis that $\bar{x}_1 = \bar{x}_2$ is accepted against the alternative $\bar{x}_1 \neq \bar{x}_2$, when $|t| \leqslant t_{\alpha/2, n_1+n_2-2}$.

(*b*) For independent random samples from two normal populations whose *variances are significantly different* the Smith–Satterthwaite test[6] examines the null hypothesis of equal means with the statistic

$$t' = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{s_1^2/n_1 + s_2^2/n_2}}$$

The sampling distribution of t' is approximated by the t distribution with the degrees of freedom given by

$$\frac{(s_1^2/n_1 + s_2^2/n_2)^2}{\dfrac{(s_1^2/n_1)^2}{n_1-1} + \dfrac{(s_2^2/n_2)^2}{n_2-1}}$$

(iii) *Method of dealing with run-outs and lug-end failures*

A run-out or lug-end failure precludes that specimen experiencing a failure in the test section. In such a case the mean and variance calculated for the test section failures which actually occurred are biassed estimators of the population values for such failures. The method used to upgrade the values of the means and variances consisted of adding corrections based on the use of maximum likelihood estimators.[7] For uncensored samples the maximum likelihood method gives a biassed estimate of the population variance for a normal distribution by a factor of $n/(n-1)$; this factor was applied to the computed variances when calculating the F and t values as above.

There were 11 country/stress level combinations (excluding those below 8 ksi (55 MPa)) which contained run-outs and/or lug-end failures. For three of these combinations the computed variance (and using the appropriate factor) was *less* than the variance calculated using the run-out/lug-end failure lives as obtained. This anomoly arose only when the group of results contained one run-out or lug-end failure; the failure of the model is attributed to the data inadequately representing a normal distribution. These three combinations (UK1 and UK at 10 ksi (69 MPa), and UK2 at 9 ksi (62 MPa)) were not used in deriving the results given in Tables 11 and 12.

C. One-way Analysis of Variance

This analysis examines whether, at each stress level, the total variability of the combined data is due entirely to the variations within the various country samples (error), or is due partly to differences among the means of the various countries. The model used to express the observations is:

$$x_{ik} = \mu + a_i + e_{ik}$$

where x_{ik} = the kth observation of the ith country,

μ = grand mean,

a_i = treatment (country) effects,

e_{ik} = "errors".

The analysis assumes that the random variables x_{ik} are independent and that the individual populations (countries) are normally distributed and have common variance. (Note that the assumption of common variance is invalid in some cases – see Tables 5 to 11 – but even so the method is considered sufficiently robust for the present purpose.)

Since the Mean Square Error (MSE) provides an estimate of the total population variance, σ^2, and the Mean Square of Treatments (Countries) provides an estimate of σ^2 plus whatever variability there may be among the individual population means, the variance ratio (F-test) indicates the probability of a "treatments" (i.e. countries) contribution to total variability.

The Error Sum of Squares (SSE) = $\Sigma((n-1)s^2)$.

The Treatment (Country) Sum of Squares (SS(Tr)) = $\Sigma n\bar{x}^2 - \Sigma(n\bar{x})^2/\Sigma n$.

F = MS(Tr)/MSE.

An example of these calculations is given below for the case: four "countries", test section failures + run-outs, AUS results shifted using LOGN = 9·123 – 0·0003373 (psi), stress level 12 ksi (83 MPa).

Country	n	$\bar{x}$	s^2	$n\bar{x}$	$n\bar{x}^2$	$(n-1)s^2$
UK1	3	5·16127	0·012094	15·43831	79·91612	0·024187
UK2	7	5·20418	0·028376	36·42926	189·58443	0·170258
CAN	5	5·20982	0·006472	26·04910	135·71112	0·025888
AUS	4	4·89099	0·023733	19·56396	95·68713	0·071198

SS(Tr) = 0·30165

SSE = 0·29153

ANOVA

Source of variation	Degrees of freedom	Sum of squares	Mean square	F
Between countries	3	0·30165	0·10055	5·17
Error	15	0·29153	0·01944	

$F_{0.05,3,15}$ = 3·29.
$F_{0.01,3,15}$ = 5·42.

Thus, there is a significant difference among the country means at the 5% level.

Where the ANOVA has indicated a significant difference among the means of the various countries, as in the example above, the mean(s) causing this difference may be determined by contrasting the mean of each country against the grand mean of the other countries.

Effective Contrast, C, is defined as

$$\bar{x}_i - \bar{x}_{others}.$$

Assuming independence of the x's, and common variance,

$$V(C) = (\sigma^2/n_i) + (\sigma^2/\Sigma n_{\text{others}}).$$

Thus, to compare C with the error, a squared Contrast must be defined as:

$$\text{S of Contrast} = C^2 \,.\, (n_i \Sigma n_{\text{others}}) \div (n_i + \Sigma n_{\text{others}}).$$

$$\text{Then, SS(Others)} = \text{SS(Tr)} - \text{S of Contrast}.$$

A refined ANOVA then determines the means contributing to the significant differences. The table below gives an example of this calculation for the case shown in the table above.

Contrast	C	$\dfrac{n_i \Sigma n_{\text{others}}}{n_i + \Sigma n_{\text{others}}}$	Square of Contrast
UK1 *v.* others	0·03363	48/19	0·00286
UK2 *v.* others	0·11277	84/19	0·05623
CAN *v.* others	0·10432	70/19	0·04009
AUS *v.* others	0·30649	60/19	0·29664

Refined ANOVAs

Source of variation	Degrees of freedom	Sum of squares	Mean square	F	
UK1 *v.* others	1	0·00286	0·00286	< 1	
Among others	2	0·29879	0·14939	7·69	$F_{0.05,2,15} = 3{\cdot}68$
Error	15	0·29153	0·01944		
UK2 *v.* others	1	0·05623	0·05623	2·89	$F_{0.05,1,15} = 4{\cdot}54$
Among others	2	0·24542	0·12271	6·31	$F_{0.05,2,15} = 3{\cdot}68$
Error	15	0·29153	0·01944		
CAN *v.* others	1	0·04009	0·04009	2·06	$F_{0.05,1,15} = 4{\cdot}54$
Among others	2	0·26155	0·13078	6·73	$F_{0.05,2,15} = 3{\cdot}68$
Error	15	0·29153	0·01944		
AUS *v.* others	1	0·29664	0·29664	15·26	$F_{0.05,1,15} = 4{\cdot}54$
Amongh others	2	0·00501	0·00250	< 1	
Error	15	0·29153	0·01944		

Conclusion: the mean of AUS is significantly different from the means of the others.

D. Two-way Analysis of Variance

This analysis examines whether, over all the data from the various countries, the variability of the combined data is due to the variations within each country's data (error), or whether part of the total variability arises from differences between each country's data. That is, the analysis examines any "country" effect after allowing for any stress level effect.

The method used[8] considers a two-way classification with unequal numbers (in each country stress cell) and no interaction (between countries and stresses). The model used is:

$$x_{ijk} = \mu + a_i + b_j + e_{ijk}$$

where x_{ijk} = kth observation in the (i,j)th country/stress cell,

μ = grand mean,

a_i = treatment (country) effects,

b_j = block (stress level) effects,

e_{ijk} = "errors".

The method is an extension of the one-way analysis outlined above and it makes the same assumptions.

An example of the two-way ANOVA is given below for the case: four "countries", test section failures + run-outs, AUS results shifted using LOGN = 9·123 − 0·0003373S (psi).

ANOVA (two-way)

Source of variation	Degrees of freedom	Sum of squares	Mean square	F	
Countries—eliminating stresses	3	0·82515	0·27505	1·17	$F_{0.05,3,80}$ = 2·73
Stresses—ignoring countries	3	14·46274	4·82091	20·46	$F_{0.05,3,80}$ = 2·73
Error	80	18·84572	0·23557		
Total	86	34·13361			

Thus, there is no significant difference between the data from the various countries.

The possibility of interactions between countries and stresses was examined by using the model:

$$x_{ijk} = \mu + a_i + b_j + c_{ij} + e_{ijk}$$

where x_{ijk}, a_i, b_j, e_{ijk} = as above,

c_{ij} = treatment/block (country/stress) interaction effect in the (i,j)th cell.

For this model a refined two-way ANOVA may be determined and the table below gives the results for the case mentioned above.

Refined ANOVA (two-way)

Source of variation	Degrees of freedom	Sum of squares	Mean square	F	
Countries—eliminating stresses	3	0·82515	0·27505	1·13	$F_{0.05,3,71}$ = 2·74
Stresses—eliminating countries	3	14·35024	4·78341	19·68	$F_{0.05,3,71}$ = 2·74
Interaction	9	1·70403	0·18934	< 1	
Error	71	17·25418	0·24302		
Total	86	34·13361			

From this table it is clear that there is no significant country/stress interaction.

TABLE 1

Fatigue Test Results—UK Series 1

Mean stress 16,000 p.s.i. (110 MPa)

Specimen number	Alternating stress (S_a)		Cycles to failure (N_f)	Remarks
	p.s.i.	MPa		
17/1	14,000	97	53,100	Test section failure
17/5	14,000	97	68,600	Test section failure
15/6	14,000	97	74,000	Test section failure
22/8	14,000	97	75,600	Test section failure
3/7	12,000	83	125,000	Test section failure
17/4	12,000	83	125,500	Test section failure
12/1	12,000	83	194,200	Test section failure
9/1	10,000	69	184,600	Test section failure
27/10	10,000	69	193,600	Test section failure
26/2	10,000	69	267,500	Test section failure
22/10	10,000	69	398,600	Test section failure
28/1	10,000	69	4,523,300	Lug-end failure
29/8	9,000	62	200,500	Test section failure
4/1	9,000	62	369,400	Test section failure
33/7	9,000	62	375,000	Lug-end failure
5/10	9,000	62	465,200	Test section failure
4/6	9,000	62	514,600	Lug-end failure
6/3	9,000	62	618,500	Test section failure
10/5	9,000	62	3,863,300	Test section failure
3/9	8,000	55	605,000	Test section failure
12/4	8,000	55	783,300	Test section failure
2/3	8,000	55	4,914,000	Lug-end failure
12/5	8,000	55	10,617,000	Lug-end failure

TABLE 2

Fatigue Test Results—UK Series 2

Mean stress = 16,000 p.s.i. (110 MPa)

Specimen number	Alternating stress (S_a)		Cycles to failure (N_f)	Remarks
	p.s.i.	MPa		
4/7	14,000	97	61,600	Test section failure
13/3	14,000	97	90,900	Test section failure
20/10	14,000	97	91,300	Test section failure
33/6	14,000	97	96,800	Test section failure
24/4	14,000	97	105,400	Test section failure
2/10	14,000	97	108,100	Test section failure
25/2	14,000	97	120,100	Test section failure
6/9	12,000	83	76,900	Test section failure
25/5	12,000	83	141,600	Test section failure
3/2	12,000	83	142,200	Test section failure
32/10	12,000	83	162,600	Test section failure
5/4	12,000	83	192,600	Test section failure
23/3	12,000	83	224,800	Test section failure
14/7	12,000	83	246,500	Test section failure
2/9	10,000	69	130,900	Test section failure
30/8	10,000	69	142,300	Test section failure
8/2	10,000	69	172,100	Test section failure
13/10	10,000	69	196,900	Test section failure
24/7	10,000	69	203,800	Test section failure
10/1	10,000	69	208,300	Test section failure
33/4	10,000	69	225,300	Test section failure
20/1	10,000	69	3,600,700	Test section failure
17/8	9,000	62	232,500	Test section failure
8/10	9,000	62	234,700	Test section failure
22/1	9,000	62	249,900	Test section failure
1/4	9,000	62	288,100	Test section failure
28/4	9,000	62	491,700	Test section failure
4/3	9,000	62	499,200	Test section failure
31/8	9,000	62	612,800	Test section failure
26/7	9,000	62	6,405,100	No failure

TABLE 3

Fatigue Test Results—Canada

Mean stress = 16,000 p.s.i. (110 MPa)

Specimen number	Alternating stress (S_a)		Cycles to failure (N_f)	Remarks
	p.s.i.	MPa		
32/5	14,000	97	66,000	Test section failure
15/4	14,000	97	72,000	Test section failure
20/8	14,000	97	83,000	Test section failure
5/5	14,000	97	115,000	Test section failure
30/9	12,000	83	135,000	Test section failure
F19/1	12,000	83	138,000	Test section failure
23/6	12,000	83	162,000	Test section failure
10/6	12,000	83	175,000	Test section failure
22/3	12,000	83	212,000	Test section failure
25/7	10,000	69	237,000	Test section failure
24/3	10,000	69	242,000	Test section failure
12/9	10,000	69	378,000	Retest. Test section failure
7/3	10,000	69	475,000	Test section failure
F29/1	10,000	69	10,447,000	Test section failure
26/8	9,000	62	301,000	Test section failure
33/10	9,000	62	357,000	Test section failure
6/10	9,000	62	385,000	Test section failure
13/7	9,000	62	554,000	Test section failure
17/10	9,000	62	20,117,000	No failure
14/2	9,000	62	30,603,000	No failure
31/2	8,000	55	379,000	Test section failure
9/9	8,000	55	400,000	Test section failure
28/7	8,000	55	454,000	Test section failure
21/6	8,000	55	608,000	Test section failure
8/4	8,000	55	10,318,000	No failure
12/9	8,000	55	20,308,000	No failure
3/8	7,000	48	672,000	Test section failure
F1/1	7,000	48	777,000	Test section failure
2/5	7,000	48	2,510,000	Test section failure
27/4	7,000	48	20,144,000	No failure
4/2	7,000	48	42,962,000	Lug-end failure

TABLE 4

Fatigue Test Results—Australia

Mean stress 16,000 p.s.i. (110 MPa)

Specimen number	Alternating stress (S_a) p.s.i.	Alternating stress (S_a) MPa	Cycles to failure (N_f)	Lugs expanded	Remarks
4/10	13,900	96	71,000	Yes	Retest. Test section failure
21/5	13,700	94	51,400	Yes	Test section failure
29/9	13,700	94	72,500	Yes	Test section failure
F30/1	13,600	94	63,000	No	Test section failure
28/10	13,600	94	90,900	No	Test section failure
32/2	12,500	86	96,000	Yes	Retest. Test section failure
5/6	12,500	86	581,800	Yes	Retest. Test section failure
F2/1	11,700	81	66,900	Yes	Test section failure
31/4	11,700	81	90,700	No	Test section failure
19/4	11,700	81	97,300	No	Test section failure
8/5	11,700	81	157,600	Yes	Test section failure
7/2	11,000	76	248,200	Yes	Retest. Test section failure
10/9	10,800	74	59,200	Yes	Test section failure
14/3	10,800	74	82,100	Yes	Lug-end failure
F6/1	10,800	74	111,200	Yes	Test section failure
4/4	10,800	74	142,000	Yes	Test section failure
20/7	10,800	74	160,000	Yes	Retest. Test section failure
1/3	10,700	74	110,500	Yes	Test section failure
3/10	10,650	73	275,200	Yes	Lug-end failure
1/8	10,150	70	87,200	No	Test section failure
32/2	10,150	70	1,093,900	Yes	Retest. No failure
4/10	10,150	70	1,100,000	Yes	Retest. No failure
5/6	10,150	70	2,918,800	Yes	No failure
3/5	10,000	69	129,500	No	Lug-end failure
26/3	9,800	68	136,500	No	Lug-end failure
25/8	9,800	68	160,500	Yes	Test section failure
22/9	9,800	68	164,300	No	Lug-end failure
23/5	9,800	68	2,328,000	Yes	Retest. Test section failure
12/10	9,800	68	9,855,500	Yes	Test section failure

Continued

TABLE 4

Fatigue Test Results—Australia

Mean stress = 16,000 p.s.i. (110 MPa)

Specimen number	Alternating stress (S_a) p.s.i.	Alternating stress (S_a) MPa	Cycles to failure (N_f)	Lugs expanded	Remarks
4/10	13,900	96	71,000	Yes	Retest. Test section failure
21/5	13,700	94	51,400	Yes	Test section failure
29/9	13,700	94	72,500	Yes	Test section failure
F30/1	13,600	94	63,000	No	Test section failure
28/10	13,600	94	90,900	No	Test section failure
32/2	12,500	86	96,000	Yes	Retest. Test section failure
5/6	12,500	86	581,800	Yes	Retest. Test section failure
F2/1	11,700	81	66,900	Yes	Test section failure
31/4	11,700	81	90,700	No	Test section failure
19/4	11,700	81	97,300	No	Test section failure
8/5	11,700	81	157,600	Yes	Test section failure
7/2	11,000	76	248,200	Yes	Retest. Test section failure
10/9	10,800	74	59,200	Yes	Test section failure
14/3	10,800	74	82,100	Yes	Lug-end failure
F6/1	10,800	74	111,200	Yes	Test section failure
4/4	10,800	74	142,000	Yes	Test section failure
20/7	10,800	74	160,000	Yes	Retest. Test section failure
1/3	10,700	74	110,500	Yes	Test section failure
3/10	10,650	73	275,200	Yes	Lug-end failure
1/8	10,150	70	87,200	No	Test section failure
32/2	10,150	70	1,093,900	Yes	Retest. No failure
4/10	10,150	70	1,100,000	Yes	Retest. No failure
5/6	10,150	70	2,918,800	Yes	No failure
3/5	10,000	69	129,500	No	Lug-end failure
26/3	9,800	68	136,500	No	Lug-end failure
25/8	9,800	68	160,500	Yes	Test section failure
22/9	9,800	68	164,300	No	Lug-end failure
23/5	9,800	68	2,328,000	Yes	Retest. Test section failure
12/10	9,800	68	9,855,500	Yes	Test section failure

Continued

TABLE 4—continued

Specimen number	Alternating stress (S_a) p.s.i.	Alternating stress (S_a) MPa	Cycles to failure (N_f)	Lugs expanded	Remarks
15/7	9,000	62	231,300	Yes	Test section failure
2/7	9,000	62	436,200	Yes	Test section failure
24/8	9,000	62	684,200	Yes	Test section failure
9/8	9,000	62	1,016,300	Yes	Test section failure
20/7	9,000	62	10,893,000	Yes	No failure
7/2	9,000	62	13,674,200	Yes	No failure
F13/1	8,500	59	182,600	No	Test section failure
32/2	8,360	58	6,751,000	Yes	No failure
9/2	8,000	55	209,300	No	Lug-end failure
27/6	7,800	54	300,100	No	Lug-end failure
23/5	7,800	54	21,074,000	Yes	No failure
17/2	6,900	48	325,500	No	Lug-end failure
12/6	6,000	41	334,100	Yes	Test section failure
6/6	6,000	41	351,000	No	Lug-end failure
20/6	5,080	35	717,200	No	Lug-end failure
4/10	5,000	34	5,200,000	Yes	No failure
5/7	4,000	28	710,500	Yes	Lug-end failure
7/10	4,000	28	10,456,400	Yes	No failure

TABLE 5

Results of Significance Tests on Pairwise Means (*t*-test) and Variances (*F*-test)

Data Group: Test Section Failures
AUS results shifted using LOGN = 7·533 − 0·0002085 S (p.s.i.)
13·7, 13·6 ksi results shifted to 14 ksi
11·7 ksi results shifted to 12 ksi
10·15, 9·8 ksi results shifted to 10 ksi
Results below 9 ksi ignored

Comparison of:	Statistical test	Alternating stress (S_a)— ksi (MPa)				
		14 (97)	12 (83)	10 (69)	9 (62)	8 (55)
UK1–UK2	*F*	NS	NS	NS	*	
	t	*	NS	NS	NS(t')	
UK1–CAN	*F*	NS	NS	*	*	NS†
	t	NS	NS	NS(t')	NS(t')	NS†
UK2–CAN	*F*	NS	NS	NS	NS	
	t	NS	NS	NS	NS	
UK–CAN	*F*	NS	NS	NS	NS	NS†
	t	NS	NS	NS	NS	NS†
UK1–AUS	*F*	NS	NS	**	NS	
	t	NS	NS	NS(t')	NS	
UK2–AUS	*F*	NS	NS	NS	NS	
	t	**	*	NS	NS	
UK–AUS	*F*	NS	NS	*	NS	
	t	*	*	NS(t')	NS	
CAN–AUS	*F*	NS	NS	NS	NS	
	t	NS	**	NS	NS	

NS—Difference not significant at 5% level.
*—Difference significant at 5% level.
**—Difference significant at 1% level.
(t')—Modified t-test (Appendix 2).
†—Same result because UK = UK1 at 8 ksi.

TABLE 6

Results of Significance Tests on Pairwise Means (*t*-test) and Variances (*F*-test)

Data Group: Test Section Failures
AUS results shifted using LOGN = 7·270 − 0·0001867 S (psi)
13·7, 13·6 ksi results shifted to 14 ksi
11·7 ksi results shifted to 12 ksi
9·8–10·8 ksi results shifted to 10 ksi
8·5 ksi results shifted to 9 ksi
Result at 6 ksi ignored

Comparison of:	Statistical test	Alternating stress (S_a)—ksi (MPa)				
		14 (97)	12 (83)	10 (69)	9 (62)	8 (55)
UK1–UK2	*F*	**NS**	**NS**	**NS**	*****	
	t	*****	**NS**	**NS**	**NS(*t′*)**	
UK1–CAN	*F*	**NS**	**NS**	*****	*****	**NS·**
	t	**NS**	**NS**	**NS(*t′*)**	**NS(*t′*)**	**NS·**
UK2–CAN	*F*	**NS**	**NS**	**NS**	**NS**	
	t	**NS**	**NS**	**NS**	**NS**	
UK–CAN	*F*	**NS**	**NS**	**NS**	**NS**	**NS·**
	t	**NS**	**NS**	**NS**	**NS**	**NS·**
UK1–AUS	*F*	NS	NS	*	NS	
	t	NS	NS	NS(*t′*)	NS	
UK2–AUS	*F*	NS	NS	NS	NS	
	t	**	*	NS	NS	
UK–AUS	*F*	NS	NS	NS	NS	
	t	*	*	NS	NS	
CAN–AUS	*F*	NS	NS	NS	NS	
	t	NS	*	NS	NS	

NS—Difference not significant at 5% level.

*—Difference significant at 5% level.

**—Difference significant at 1% level.

(*t′*)—Modified *t*-test (Appendix 2).

·—Same result because UK = UK1 at 8 ksi.

Bold type—Results same as Table 5.

TABLE 7

Results of Significance Tests on Pairwise Means (*t*-test) and Variances (*F*-test)

Data Group: Test Section Failures + run-outs
AUS results shifted using LOGN = 8·826 − 0·0003114 S (p.s.i.)
13·7, 13·6 ksi results shifted to 14 ksi
11·7 ksi results shifted to 12 ksi
9·8–10·15 ksi results shifted to 10 ksi
Results below 9 ksi ignored

Comparison of:	Statistical test	Alternating stress (S_a)—ksi (MPa) 14 (97)	12 (83)	10 (69)	9 (62)	8 (55)
UK1–UK2	*F*	NS	NS	NS	NS	
	t	*	NS	NS	NS	
UK1–CAN	*F*	NS	NS	*	NS	NS[+]
	t	NS	NS	NS(*t′*)	NS	NS[+]
UK2–CAN	*F*	NS	NS	NS	NS	
	t	NS	NS	NS	NS	
UK–CAN	*F*	NS	NS	NS	*	NS[+]
	t	NS	NS	NS	NS(*t′*)	NS[+]
UK1–AUS	*F*	NS	NS	*	NS	
	t	NS	NS	NS(*t′*)	NS	
UK2–AUS	*F*	NS	NS	NS	NS	
	t	**	*	NS	NS	
UK–AUS	*F*	NS	NS	*	NS	
	t	**	**	NS(*t′*)	NS	
CAN–AUS	*F*	NS	NS	NS	NS	
	t	*	**	NS	NS	

NS—Difference not significant at 5% level.

*—Difference significant at 5% level.

**—Difference significant at 1% level.

(*t′*)—Modified *t*-test (Appendix 2).

+—Same result because UK = UK1 at 8 ksi.

Bold type—Results same as Table 5 (no run-outs).

TABLE 8

Results of Significance Tests on Pairwise Means (*t*-test)

and Variances (*F*-test)

Data Group: Test Section Failures + Run-outs
AUS results shifted using LOGN = 9·123 − 0·0003373 S (p.s.i.)
13·7, 13·6 ksi results shifted to 14 ksi
11·7 ksi results shifted to 12 ksi
9·8–10·8 ksi results shifted to 10 ksi
7·8–8·5 ksi results shifted to 8 ksi
Results below 7·8 ksi ignored

Comparison of:	Statistical test	Alternating stress (S_a)—ksi (MPa)				
		14 (97)	12 (83)	10 (69)	9 (62)	8 (55)
UK1–UK2	*F*	**NS**	**NS**	**NS**	**NS**	
	t	*	**NS**	**NS**	**NS**	
UK1–CAN	*F*	**NS**	**NS**	*	**NS**	**NS**·
	t	**NS**	**NS**	**NS(*t*′)**	**NS**	**NS**·
UK2–CAN	*F*	**NS**	**NS**	**NS**	**NS**	
	t	**NS**	**NS**	**NS**	**NS**	
UK–CAN	*F*	**NS**	**NS**	**NS**	*	**NS**·
	t	**NS**	**NS**	**NS**	**NS(*t*′)**	**NS**·
UK1–AUS	*F*	NS	NS	*	**NS**	NS×
	t	NS	NS	NS(*t*′)	**NS**	NS×
UK2–AUS	*F*	NS	NS	NS	**NS**	
	t	**	*	NS	**NS**	
UK–AUS	*F*	NS	NS	NS	**NS**	NS×
	t	**	**	NS	**NS**	NS×
CAN–AUS	*F*	NS	NS	NS	**NS**	NS
	t	*	**	NS	**NS**	NS

NS – Difference not significant at 5% level.

* Difference significant at 5% level.

** Difference significant at 1% level.

(*t*′) Modified *t*-test (Appendix 2).

·, × Same result because UK = UK1 at 8 ksi.

Bold type Results same as Table 7.

TABLE 9

Results of Significance Tests on Pairwise Means (*t*-test) and Variances (*F*-test)

Data Group: Test Section Failures + Run-outs + Lug-end Failures
AUS results shifted using LOGN = 8·472 − 0·0002867 S (p.s.i.)
13·7, 13·6 ksi results shifted to 14 ksi
11·7 ksi results shifted to 12 ksi
9·8–10·15 ksi results shifted to 10 ksi
Results below 9 ksi ignored

Comparison of:	Statistical test	Alternating stress (S_a)—ksi (MPa)				
		14 (97)	12 (83)	10 (69)	9 (62)	8 (55)
UK1–UK2	*F*	NS	NS	NS	NS	
	t	*	NS	NS	NS	
UK1–CAN	*F*	NS	NS	NS	NS	NS†
	t	NS	NS	NS	NS	NS†
UK2–CAN	*F*	NS	NS	NS	NS	
	t	NS	NS	NS	NS	
UK–CAN	*F*	NS	NS	NS	*	NS†
	t	NS	NS	NS	NS(*t*′)	NS†
UK1–AUS	*F*	NS	NS	NS	NS	
	t	NS	NS	NS	NS	
UK2–AUS	*F*	NS	NS	NS	NS	
	t	**	*	NS	NS	
UK–AUS	*F*	NS	NS	NS	NS	
	t	**	**	NS	NS	
CAN–AUS	*F*	NS	NS	NS	NS	
	t	*	**	NS	NS	

NS—Difference not significant at 5% level.

*—Difference significant at 5% level.

**—Difference significant at 1% level.

(*t*′)—Modified *t*-test (Appendix 2).

†—Same result because UK = UK1 at 8 ksi.

Bold type—Results same as Table 7.

TABLE 10

Results of Significance Tests on Pairwise Means (t-test)

and Variances (F-test)

Data Group: Test Section Failures · Run-outs · Lug-end Failures
AUS results shifted using LOGN 8·331 0·0002747 S (p.s.i.)
13·7, 13·6 ksi results shifted to 14 ksi
11·7 ksi results shifted to 12 ksi
9·8–10·8 ksi results shifted to 10 ksi
7·8–8·5 ksi results shifted to 8 ksi
Results below 7·8 ksi ignored

Comparison of:	Statistical test	Alternating stress (S_a) ksi (MPa)				
		14 (97)	12 (83)	10 (69)	9 (62)	8 (55)
UK1–UK2	F	NS	NS	NS	NS	
	t	*	NS	NS	NS	
UK1–CAN	F	NS	NS	NS	NS	NS†
	t	NS	NS	NS	NS	NS†
UK2–CAN	F	NS	NS	NS	NS	
	t	NS	NS	NS	NS	
UK–CAN	F	NS	NS	NS	*	NS†
	t	NS	NS	NS	NS(t')	NS†
UK1–AUS	F	NS	NS	NS	NS	NS×
	t	NS	NS	NS	NS	NS×
UK2–AUS	F	NS	NS	NS	NS	
	t	**	*	NS	NS	
UK–AUS	F	NS	NS	NS	NS	NS×
	t	*	**	NS	NS	NS×
CAN–AUS	F	NS	NS	NS	NS	NS
	t	*	**	NS	NS	NS

NS – Difference not significant at 5% level.

* – Difference significant at 5% level.

** – Difference significant at 1% level.

(t') – Modified t-test (Appendix 2).

†, × — Same result because UK UK1 at 8 ksi.

Bold type— Results same as Table 9.

TABLE 11

Results of Significance Tests on Pairwise Means (t-test) and Variances (F-test)

Data Group: Test Section Failures + Upgraded Lives (using Maximum Likelihood Method) for Run-outs and Lug-End Failures
AUS results shifted (before upgrading) using LOGN = 8·331 − 0·0002747 S (p.s.i.)†
13·7, 13·6 ksi results shifted to 14 ksi†
11·7 ksi results shifted to 12 ksi†
9·8–10·8 ksi results shifted to 10 ksi†
7·8–8·5 ksi results shifted to 8 ksi†
Results below 7·8 ksi ignored†

Comparison of:	Statistical test	Alternating stress (S_a) ksi (MPa)				
		14 (97)	12 (83)	10 (69)	9 (62)	8 (55)
UK1–UK2	F t				NS NS	
UK1–CAN	F t				NS NS	NS[+] NS[+]
UK2–CAN	F t				NS NS	
UK–CAN	F t				* NS(t')	NS[+] NS[+]
UK1–AUS	F t			NS NS	NS NS	NS[×] NS[×]
UK2–AUS	F t			NS NS	NS NS	
UK–AUS	F t			NS NS	NS NS	NS[×] NS[×]
CAN–AUS	F t			NS NS	NS NS	NS NS

NS—Difference not significant at 5% level.

*—Difference significant at 5% level.

(t')—Modified t-test (Appendix 2).

+, ×—Same result because UK = UK1 at 8 ksi.

†—Same as Table 10.

TABLE 12

Results of Analysis of Variance at Each Stress Level for the Four 'Countries'—UK1, UK2, Canada, Australia

Data group	AUS results shifted using LOGN = A − B S (psi)		Alternating stress (S_a)—ksi (MPa)				
	Constant A	Constant B	14 (97)	12 (83)	10 (69)	9 (62)	8 (55)
Test section failures	7·533	0·0002085	* (UK2 AUS)	* (AUS)	NS	NS	
	7·270	0·0001867	* (UK2 AUS)	* (AUS)	NS	NS	
Test section failures + run-outs	8·826	0·0003114	** (UK2 AUS)	* (AUS)	NS	NS^{+}	
	9·123	0·0003373	** (UK2 AUS)	* (AUS)	NS	NS^{+}	NS
Test section failures + run-outs + lug-end failures	8·472	0·0002867	** (UK2 AUS)	* (AUS)	NS	NS$^{\times}$	
	8·331	0·0002747	** (UK2 AUS)	* (AUS)	NS	NS$^{\times}$	NS
Test section failures + upgraded lives for run-out and lug-end failures	8·331	0·0002747			NS	NS	NS

NS—Differences not significant at 5% level.

*—Differences significant at 5% level.

**—Differences significant at 1% level.

$^{+}$, $^{\times}$—Same result, no AUS shifts necessary.

( )—The countries listed in parentheses are those whose mean life was found to be significantly different from the means of the others by using Contrasts.

TABLE 13

Results of Analysis of Variance at Each Stress Level for the Three Countries—UK, Canada, Australia

Data group	AUS results shifted using LOGN = A − B S (psi) Constant A	Constant B	Alternating stress (S_a) – ksi (MPa) 14 (97)	12 (83)	10 (69)	9 (62)	8 (55)
Test section failures	7·533	0·0002085	NS	* (AUS)	NS	NS	
	7·270	0·0001867	NS	* (AUS)	NS	NS	
Test section failures + run-outs	8·826	0·0003114	* (AUS)	** (AUS)	NS	NS·	
	9·123	0·0003373	* (AUS)	** (AUS)	NS	NS·	NS
Test section failures + run-outs + lug-end failures	8·472	0·0002867	* (AUS)	** (AUS)	NS	NS×	
	8·331	0·0002747	* (AUS)	** (AUS)	NS	NS×	NS

NS—Differences not significant at 5% level.

*—Differences significant at 5% level.

**—Differences significant at 1% level.

·, ×—Same result, no AUS shifts necessary.

( )—The country listed in parentheses is that whose mean life was found to be significantly different from the means of the others by using Contrasts.

TABLE 14

Examination of Countries Involved in Significant Differences between Pairwise Means

(Information obtained from Tables 5 to 10)

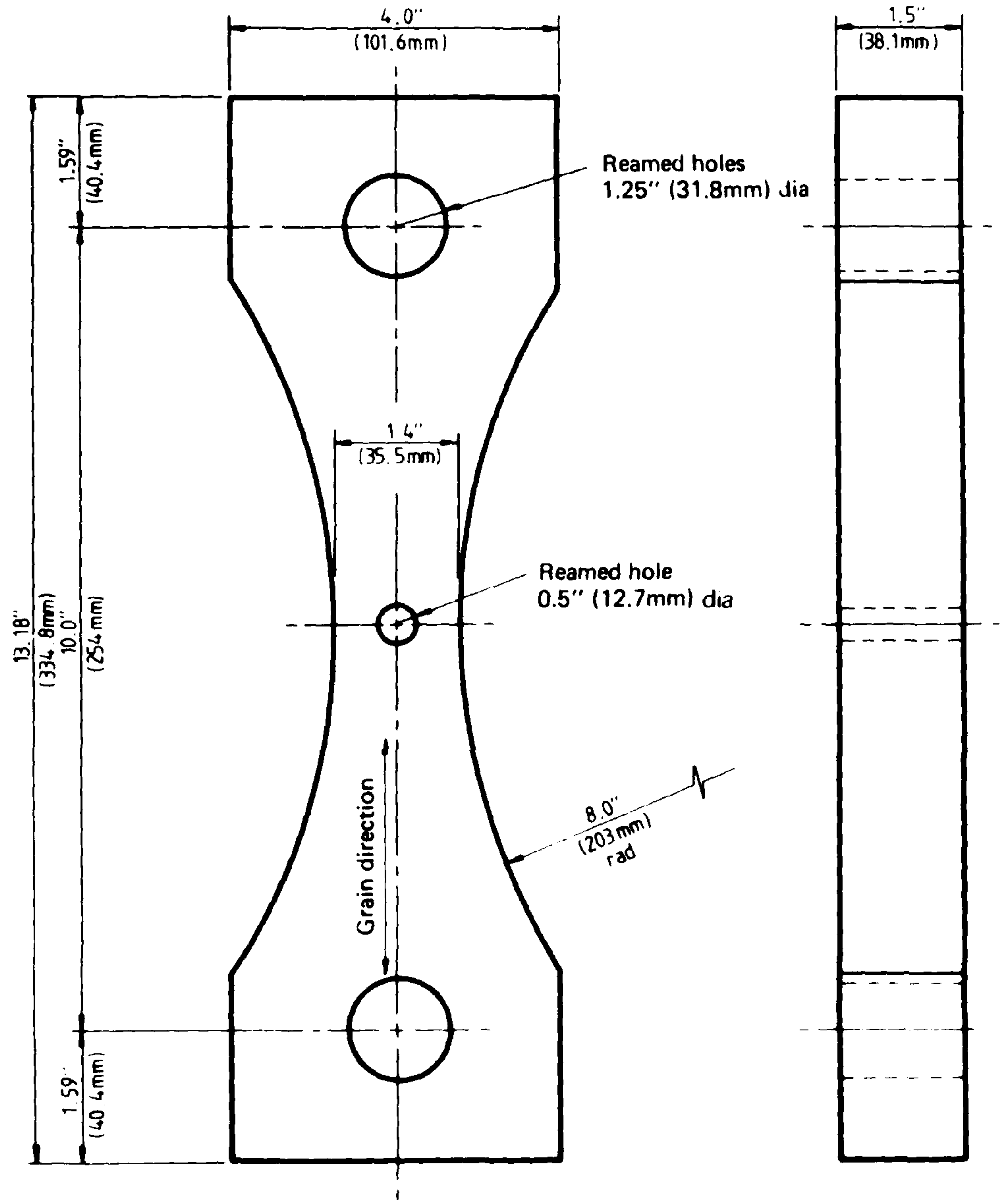
Country	Number of times Country involved in a significant difference between pairwise means, at stress level of:				
	14 ksi (97 MPa)	12 ksi (83 MPa)	10 ksi (69 MPa)	9 ksi (62 MPa)	8 ksi (55 MPa)
UK1	6	0	0	0	0
UK2	12	6	0	0	
UK	6	6	0	0	0
CAN	4	6	0	0	0
AUS	16	18	0	0	0

TABLE 15

Results of Two-way Analyses of Variance

Data group	AUS results shifted using LOGN = A − B S (psi)		No. of "countries"	Between countries (eliminating stresses)	Inter-action (countries/stresses)
	Constant A	Constant B			
Test section failures	7·533	0·0002085	3	NS	NS
			4	NS	NS
	7·270	0·0001867	3	NS	NS
			4	NS	NS
Test section failures + run-outs	8·826	0·0003114	3	NS	NS
			4	NS	NS
	9·123	0·0003373	3	NS	NS
			4	NS	NS
Test section failures + run-outs + lug-end failures	8·472	0·0002867	3	NS	NS
			4	NS	NS
	8·331	0·0002747	3	NS	NS
			4	NS	NS

NS Differences not significant at 5% level.



Surface finish – Fine machined 16 to 24 micro inches. (0.41 to 0.61μm), free from scratches. Edges of profile and holes to be sharp and free from burrs.

FIG. 1 NOMINAL DIMENSIONS OF 2L.65 SPECIMENS

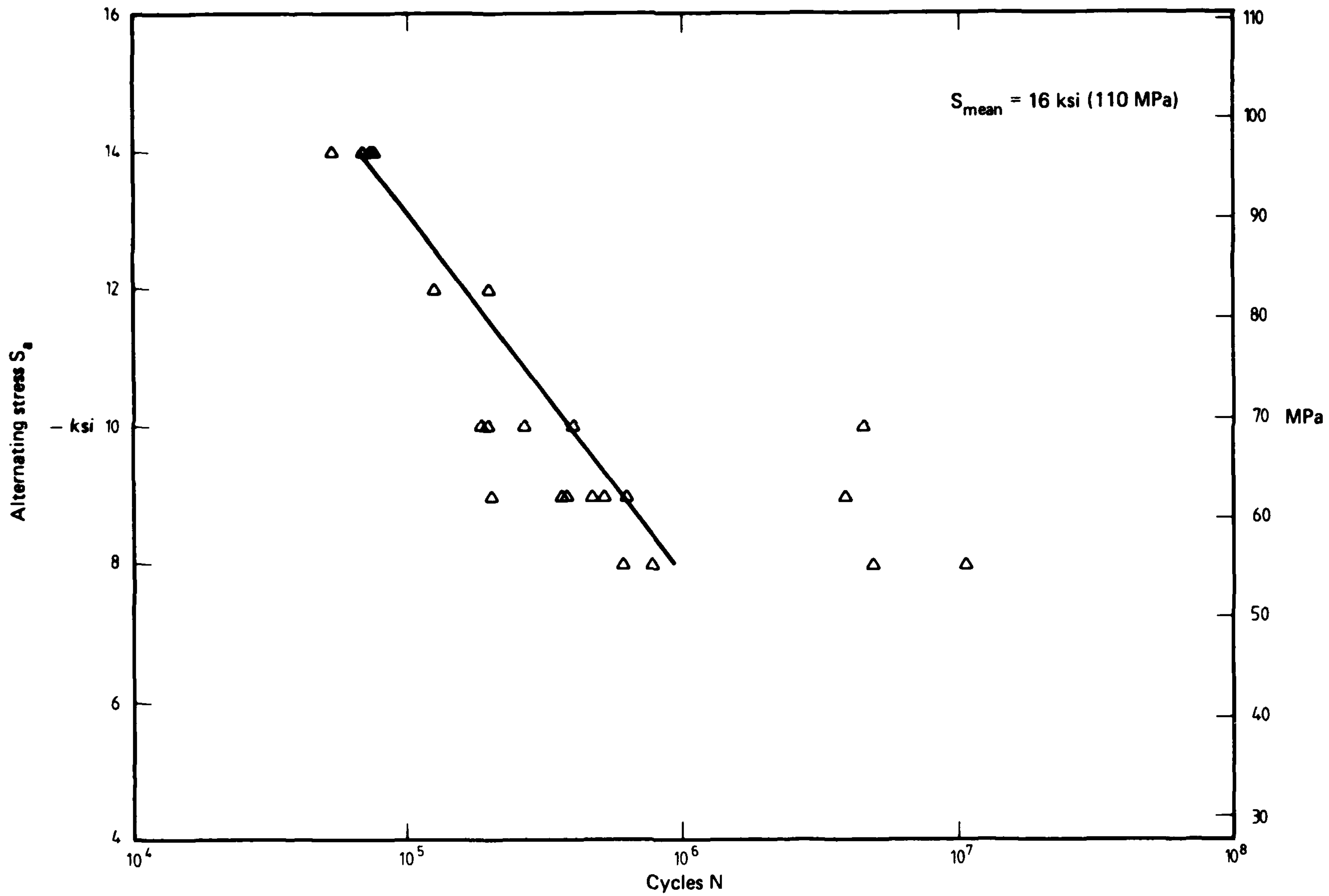


FIG. 2 FATIGUE DATA–UK SERIES 1

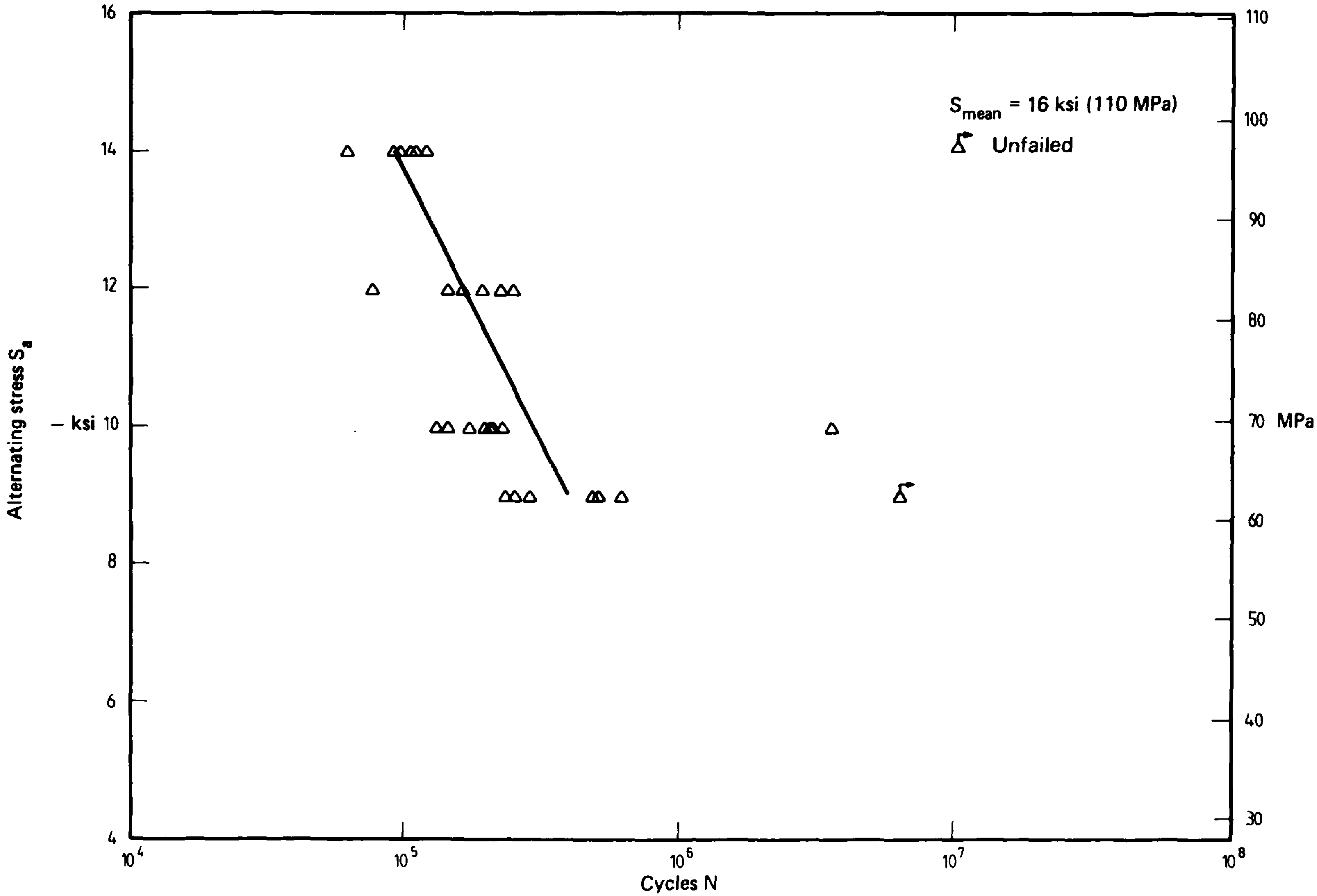


FIG. 3 FATIGUE DATA—UK SERIES 2

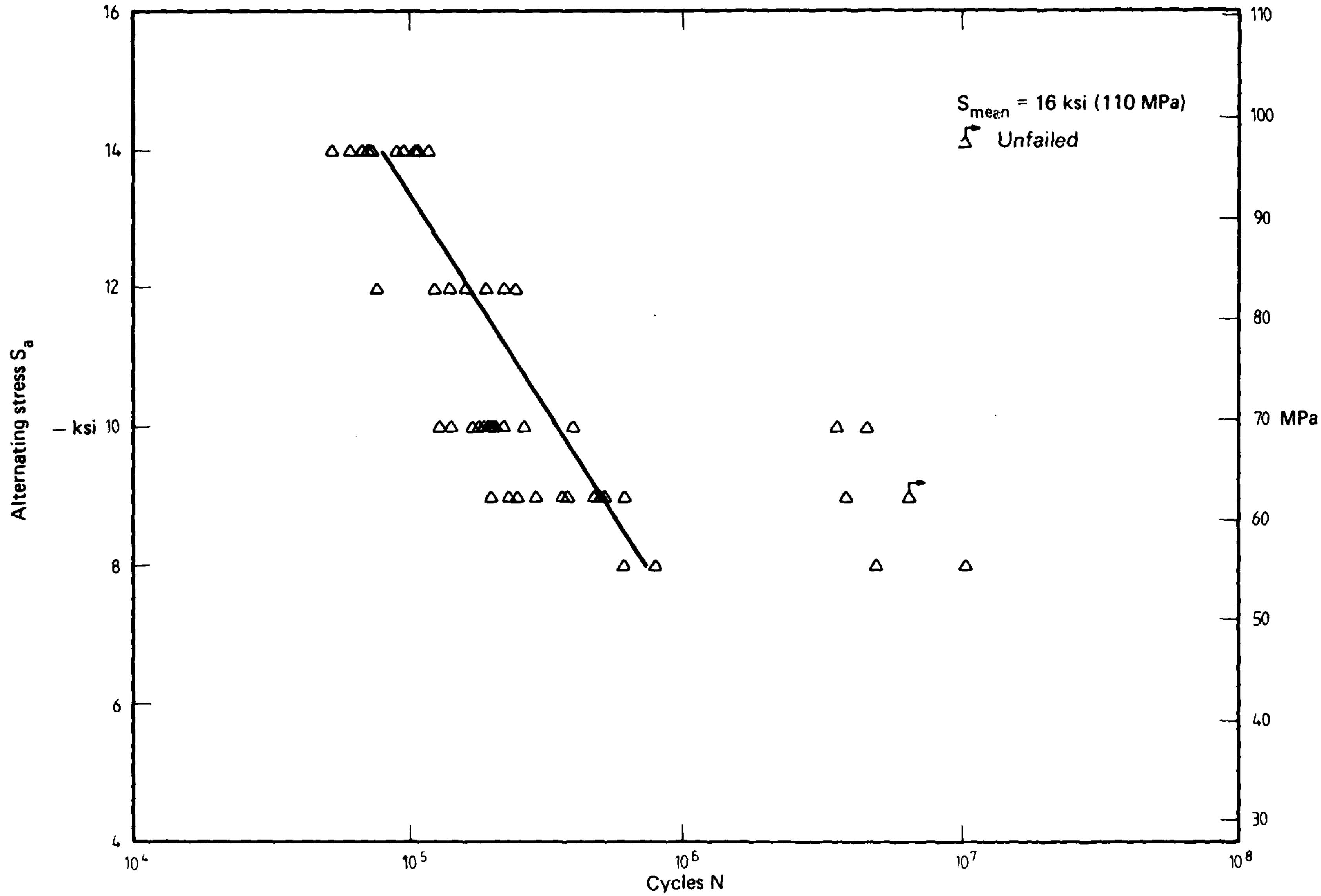


FIG. 4 FATIGUE DATA – UK (both series)

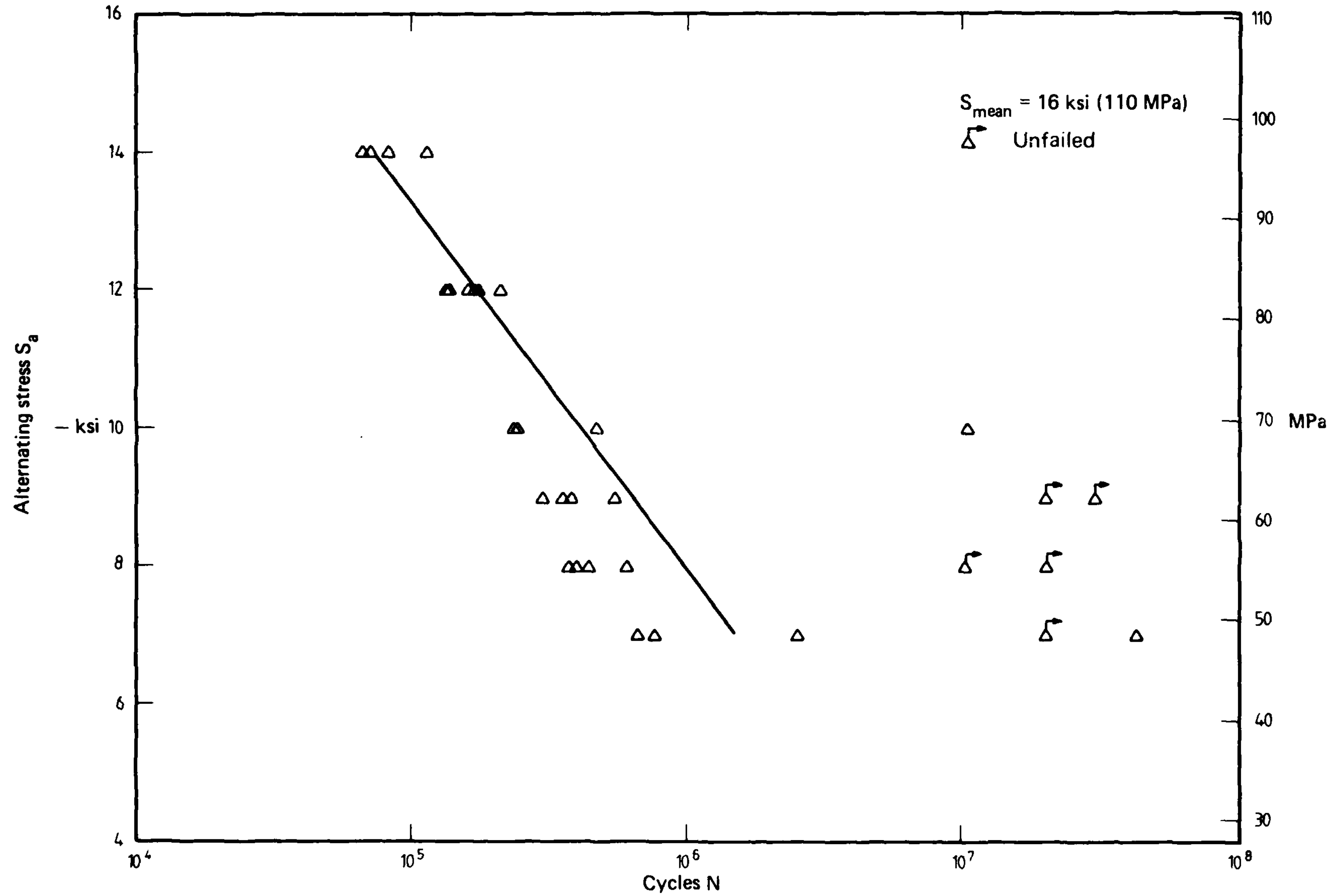


FIG. 5 FATIGUE DATA–CANADA

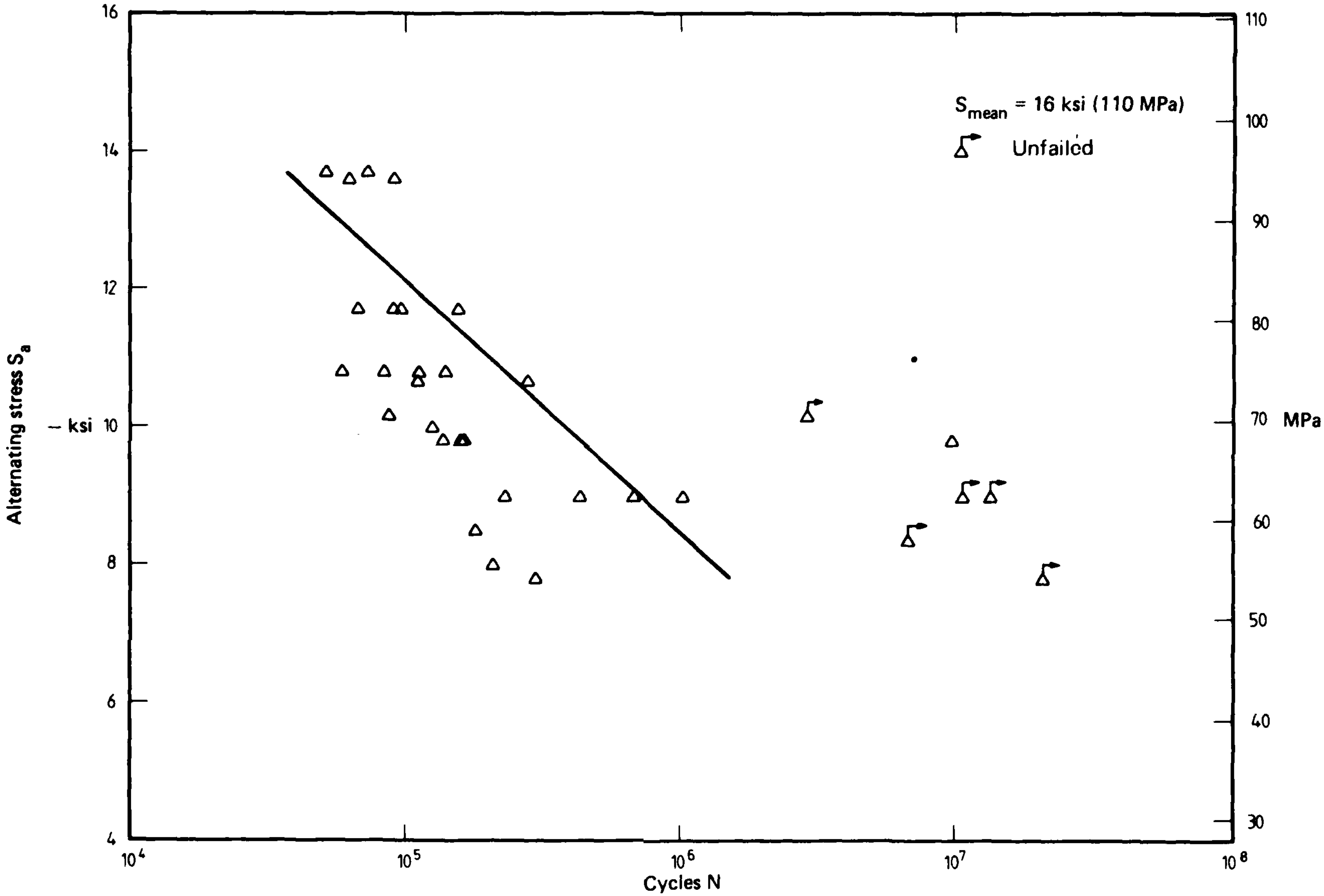


FIG. 6 FATIGUE DATA–AUSTRALIA (Excluding results below 7 · 8ksi)

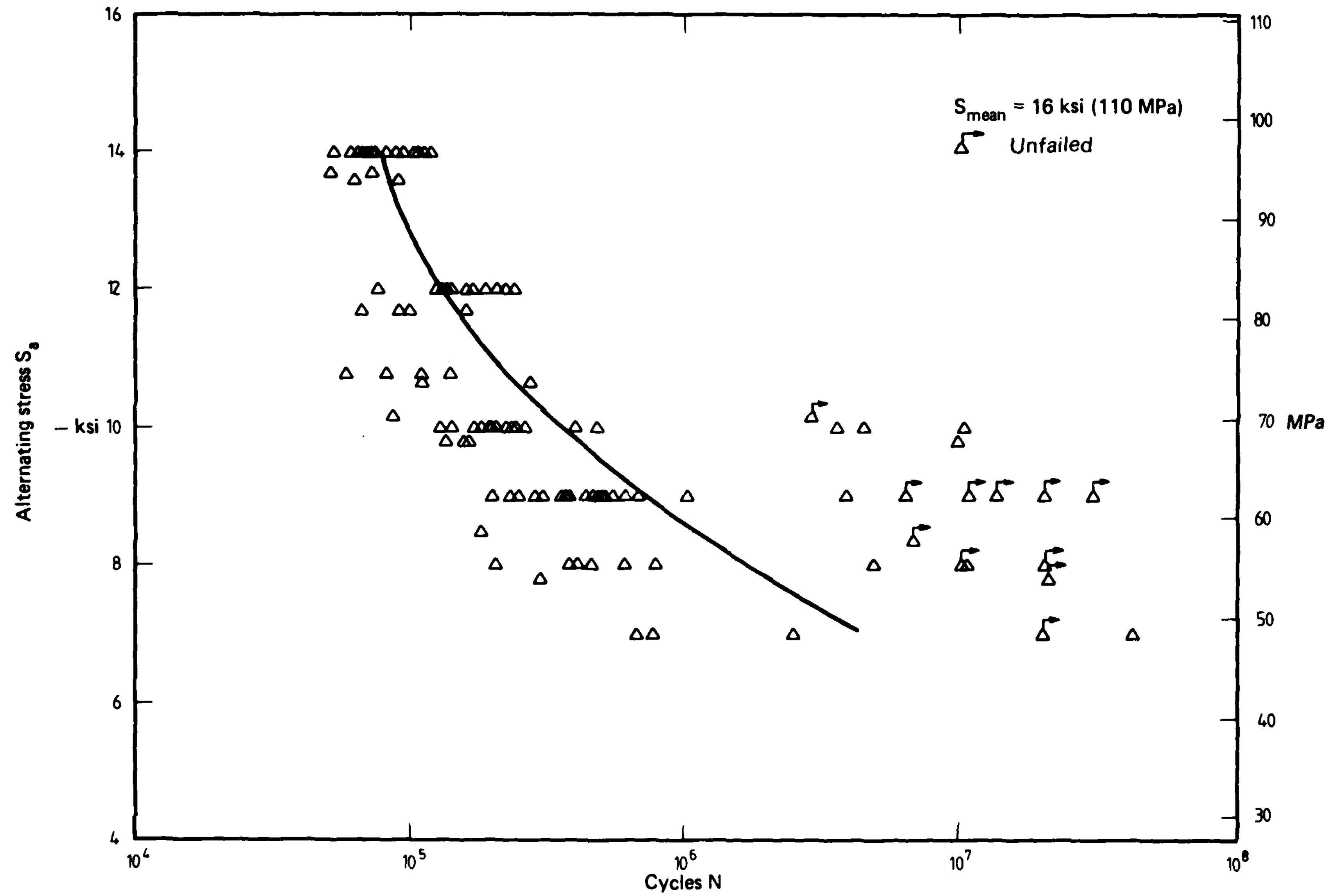


FIG. 7 FATIGUE DATA—ALL COUNTRIES

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